A Comparative Study of the Ionospheric TEC Measurements Using Global Ionospheric Maps of GPS, TOPEX radar and the Bent Model

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January 15, 1997

To be submitted to *Radio Science*

Abstract. Global Ionospheric Mapping (GIM) is a new, emerging technique for determining global ionospheric TEC (total electron content) based on measurements from a worldwide network of Global Positioning System (GPS) reveivers. In this study, GIM accuracy in specifying TEC is investigated by comparing with the direct ionospheric measurements from the Topex altimeter. A climatological model (Bent model) is also used to compare with the Topex altimeter data. We find that the GIM technique has much better agreement with Topex in TEC measurements, compared with the predictions of the climatological model. The difference between GIM and Topex in TEC measurements is very small (less than 1.5 TECU) within a 1500 km range from a reference GPS station. The RMS gradually increases with an increasing distance from the station, while the Bent model shows a constant large RMS, unrelated to any station location. Within a 1000 km distance of a GPS site (elevation angle > 25°), GIM has a good correlation (R > 0.93) to Topex with respect to TEC measurements. The slope of the linear fitting line to the dataset from two Topex cycles is 44.5° (near the ideal 45°). In the northern hemispheric regions, ionospheric specification by GIM appears to be accurate to within 3-10 TECU up to 2000+ km away from nearest GPS station (corresponding to ~ 1° elevation angle cutoff). Beyond 2000 km, GIM accuracy on average is reduced to the Bent model levels. In the equatorial region, the Bent model predictions are systematically lower (~ 5.0 TECU) than Topex values and often show a saturation at large TEC values. During ionospheric disturbed periods, GIM sometimes shows differences from Topex values due to transient variations of the ionosphere. Such problems may be improved by the continuous addition of new GPS stations in data-sparse regions. Thus, over a GPS station's measurement realm (up to 2000 km in radius), GIM can produce generally accurate TEC values. Through a spatial and temporal extrapolation of GPS-drived TEC measurements, the GIM technique provides a powerful tool for monitoring global ionospheric features in near-real time.

1. Introduction

Recently, a powerful technique for specifying global ionospheric total electron content (TEC) has been developed [Mannucci et al., 1993a and 1997; Wilson et al., 1992]. This technique is based on measurements from more than 60 GPS stations which are distributed worldwide and continuously receive dual-frequency signals from GPS satellites. Using the dispersion of the signals, we can measure the ionospheric TEC along ~480+ lines of sight and generate global TEC fits with resolution of a few minutes. The global TEC maps are very useful in monitoring (and possibly forecasting) ionospheric storms and perturbations [Coker et al., 1995; Hunsucker et al., 1995; Ho et al., 1996; Kelley et al., 1996]. Lanyi and Roth [1988] compared GPS measurements with beacon satellite observations. They found that the difference between the GPS and Faraday measurements is at 1 TECU (1 TECU = 10^{16} el/m^2).

However, in most recent studies (e.g., Coker et al., 1995; Kelley et al., 1996), TEC values are calculated along the line of sight (LOS) based on the received signal delay from a single or a few GPS stations, and then are simply projected vertically. The accuracy of the GPS technique in determining ionospheric TEC was not thoroughly evaluated. Several researchers [Brown et al., 1991; Szuszczewicz et al., 1996] have also performed comparative studies of the measured ionospheric parameters with various model predictions. While these models in general may describe the diurnal variations of the ionosphere, the predicted parameters usually exhibit large variations from the measured ionospheric values.

The Global Ionospheric Map (GIM) is a data driven model based on direct measurements by GPS stations distributed worldwide. Currently GPS provides excellent sky coverage with a full 24-satellite constellation and a relatively dense ground network. Mannucci et al. [1994] have previously made a comparison study between GPS and Topex measurements based on a small dataset. In their study, comparisons were made for the intervals when the TOPEX satellite was directly above a GPS station (within 5 degrees of the zenith angle). Overflights were examined for a total of 18 sites, using 36 separate overflights and resulting in 174 data points. Based on this restricted dataset, they found that the GIM measurements of vertical TEC were in agreement with the Topex altimeter data at the 2 - 3 TECU level in the low (< 30°) and mid-latitudes (30°- 55°). Relative to a typical daily maximum TEC value of ~80 TECU, this difference is very small.

The goal of this study is to perform such an evaluation of the GPS ionospheric calibration method, by using an extensive data base from the GPS network. The ionospheric measurements from GPS receivers, and the TOPEX dual-frequency altimeter will be intercompared with the predictions of an empirical ionosphere model (the Bent model). The discrepancies in the TEC map will be studied as a function of the distance to the nearest GPS site, such that predictions or evaluations of GIM accuracy can be made of the expected ionospheric errors anywhere on Earth. In the present study, the database has been extended to cover three Topex cycles (30 days and 750 passes). There is no data restriction for the elevation angle and distance relative to GPS stations. Hence, we have compared the models with Topex altimeter data both directly over GPS stations and also far away. In particular, the dependence of the accuracy on the distance away from the stations is examined, which is expected to be significant for the data-driven model (GIM) and immaterial for the climatological model (Bent). In the next section we will briefly describe the three separate techniques for computing ionospheric delays. The statistical results from this study will be presented in section 3. A discussion of the various factors affecting the measurements appears in section 4 and all of the results obtained from this study are summarized in the last section.

2. Techniques

In this study, the data are obtained from three types of ionospheric TEC specification methods: GIM (GPS data-driven), the Bent model (climatological) and Topex (ground truth). While the first method depends on GPS data interpolated over global scales on a gridded shell, the second is a prediction based on historical averages of years of ionospheric measurements and requires as input a few geophysical parameters. The third method is based on direct vertical measurements of the ionospheric TEC. We will compare the accuracy of specifying the global ionosphere using the data driven model (GIM) and the historical model (Bent), by relying on the Topex radar altimeter data as ground truth. The Topex measurements also contain errors. Its accuracy is estimated to be about 3 TECU [Callahan, 1993; Imel, 1994]. Hence, our accuracy predictions for GIM are conservative and represent only an upper limit.

The GIM method is a relatively new ionosphere specification technique based on data from a global GPS network of stations [Mannucci et al., 1993b; Wilson et al., 1995]. In

November of 1995, there were more than 60 permanent GPS stations around the world. These stations continuously receive dual-frequency signals from up to 8 GPS satellites simultaneously. The GPS satellites have an orbit altitude of 20200 km above the earth. The signals from the satellites will pass through the plasmasphere, the upper ionosphere and lower ionosphere to reach the ground GPS receivers. The dispersion or time delay between the two frequency signals provides a measure of integral TEC along the entire propagation path. These line-of-sight values are mapped to vertical and interpolated to generate global ionospheric TEC maps each hour or more frequently. The GIM model assumes that the ionosphere is concentrated in a thin shell at 350 km altitude. The TEC along the line-of-sight is projected vertically and has a crossing point with the shell at this height, called the ionospheric pierce point (IPP). The TEC measurements are mapped to vertical at the IPP. When the ionospheric peak height exhibits significant changes this assumption may cause some uncertainties in determining the IPP location. The ionospheric shell height has been selected based on the best result after a comparison with Topex's measurements. A Kalman-type filter is also used to estimate TEC values at grid points on the spherical shell. Because this filter has essentially a decling memory function, a measurement taken by the previous station may persist for several minutes to hours until a new measurement is made by the next station (the length of data update time is directly related to degree of station sparseness). The grid points are fixed in a solar-geomagnetic coordinate system since the ionosphere is more constant in time in that reference frame. Thus, this ionospheric mapping technique is based primarily on the observations and the interpolation method, which assumes that the ionospheric density can be well modeled on a shell. A detailed description of the GIM technique may be found in the articles of Mannucci et al. [1993a; 1997].

To compute the global ionospheric fits or maps, we initialize the shell vertex values with the Bent model at the start of each day, in order to minimize transient startup errors. The measured TECs are used to update estimates and covariances every few minutes for each of 642 vertex values distributed evenly over the globe. The TEC values at any time and any location are generated using interpolation on the gridded shell. Accompanying the global TEC map, a TEC error map is also generated simultaneously [Mannucci et al., 1993a; 1997]. The typical formal error is within 5 TECU in most global regions. Because we have assumed a shell structure of the ionosphere and are scaling LOS observations to equivalent vertical values, we expect that GIM errors will have a dependence on the elevation (or zenith) angles of the satellites as observed from a GPS station relative to the individual GPS satellites.

The Bent ionospheric model is a comprehensive empirical model [Bent et al., 1976]. This model has been extensively used for ionospheric calibrations and predictions. Because this model is based on averaged past observations spanning a significant part of the solar cycle, the model fits the ionospheric TEC measurements well over long time scales. Given monthly solar sunspot and F10.7 solar flux values, and a time, latitude, and longitude, Bent computes a prediction of vertical TEC for the given time and location. These values may be compared with directly measured values from Topex (and with interpolated values from GIM).

Topex/Poseidon mission is a US/French ocean-observing satellite that was launched on Aug. 10, 1992 [Fu et al., 1994; Mannucci et al., 1994]. There is a dual-frequency radar altimeter on board to precisely measure sea-surface height (after removing the ionospheric correction) [Imel, 1994]. Topex orbits have an average altitude of 1330 km from the Earth's surface, hence above most of the ionosphere. The period of the orbit is about 110 min. The ground track repeats every 10 days (one cycle). Since the Topex altimeter only provides TEC measurements above the ocean, there is no data available above the continental GPS stations. Topex gives a measurement of ionospheric vertical TEC every second [Imel, 1994] and we have smoothed the data into 12 second normal points. However, because Topex's orbit is relatively sun-fixed, Topex has fairly narrow local time coverage. In one cycle, its orbits shift only 2 local hours (~ 30° in longitude) at the equatorial region. Thus, Topex requires many more revolutions to generate a global map of TEC. Because Topex's dual-frequency altimeter can directly measure the ionospheric vertical TEC, we have assumed that its measurement is the ground truth for the ionospheric delay (TEC), even though it may have a systematic bias and has an estimated accuracy of 2-3 TECU [Callahan, 1993; Imel, 1994]. Its measurements will be the reference values for our comparative study. Note that the difference between Topex and GIM TEC measurements may also be due to the plasmaspheric contribution, because GPS satellites have a higher orbit. However, this difference is usually so small (1-2 TECU) that it is currently masked by measurement errors.

In this comparative study, all TEC observations are selected based on Topex's trajectories (the "truth" data). We have selected primarily two Topex cycles: Cycle 18 (March 10 - 20, 1993) and Cycle 33 (August 6 - 16, 1993) for our statistical study. We have also examined Cycle 88 (February 2 - 12, 1995) for some of the case studies. The geophysical conditions (i.e., geomagnetic indices and solar flux level) for three cycles are listed in Table 1. The three cycles are in a period of declining solar activity. Thus, cycle 18 has larger solar flux

(F10.7) than later cycles. Cycles 18 and 88 have larger geomagnetic activity (higher Dst and Kp indices) than cycle 33. The more recent cycle has a much larger number of GPS stations. We have paid close attention to the more isolated GPS stations, since one purpose of this study is to find the dependence of GIM errors on the distance from the GPS stations. For each Topex data point, one can find the GPS station which is closest to Topex's ground track trajectory. For some isolated stations, the distance between the Topex's trajectories and the closest station may be as great as 4000 km. The GIM value receives its main contribution from the measurements of the nearest station. The geometrical relationship between elevation angle and horizontal distance from a station, assuming a shell height of 350 km is shown in Figure 1. We see that an elevation angle of 0° corresponds to a distance of a distance of 2100 km relative to the station. This relates each measurement from GIM along the Topex's trajectory to its closest station. The locations are also transformed into a geomagnetic coordinate system using a tilted dipole model, considering the angle between the Earth's magnetic field axis and its rotation axis.

3. Results

In this section, the statistical results will be presented in three parts. First, we provide some typical case studies. Second, we present a statistical analysis of dependences of TEC prediction agreement on distance for two entire Topex cycles. Finally, we discuss the performance of the GIM and Bent model predictions versus Topex direct measurements for all three cycles broken down into two distance ranges: 0–1000 km and 1000–2000 km.

3.1 Typical Case Studies. Figure 2 gives two typical cases to show the ionospheric TEC specifications by the three techniques. The data have 12 sec resolution along a single Topex pass. The distance dependence is shown relative to the two closest GPS stations in the southern hemisphere. There is an upper limit of 4000 km in the distance relative to the two isolated GPS stations. Figure 2a gives the TEC measurements in an interval of about 19 minutes over a latitude range (or time) in Pass 014, Cycle 18. The TECs computed by GIM and predicted by Bent along this trajectory are also shown, relative to the station YAR1 (Yaragadee, -29.04° geog. lat., 115.35° long., -40.00° geom. lat.) in western Australia. After passing the southern equatorial anomaly with a peak at ~100 TECU, the satellite approaches the YAR1 station at -29° latitude (shown by the vertical line); the closest approach is about 800 km. Figure 2b shows the variations of the three TEC values with distance from the station. Figure 2c shows the variations of the differences of the GIM and Bent model relative to Topex TEC measurements with the distance from the station. Note that the difference between the GIM and Topex values is small (less than 5 TECU) within 1500 km of the station. Beyond 1500 km, the differences at times become large with the distance, because the large ionospheric variations in the anomaly region may not be followed. As a comparison, there is a large difference between the Bent model predictions and Topex TECs (about 14 TECU), even though both have similar profiles in Figures 2a and b. The difference does not change with distance relative to the nearest GPS station as shown in Figure 2c, because the TEC values predicted by the Bent model have no relation to this station. In contrast, the GIM values along the Topex trajectory are mainly contributed from this station through an interpolation method. Thus, measurement errors of GIM should have dependence on distance from the nearest GPS station.

Figures 2d, 2e and 2f show another example of this distance dependence. This case is selected from a Topex trajectory in Pass 182, Cycle 88 relative to the station EISL (Easter Island, -27.15° Lat., -109.38° long.) located in south-east Pacific ocean. Figure 2d shows the latitude variation of the three TEC values in a period of ~ 18 minutes. After passing the southern ionospheric peak, the GIM measurements fit Topex very well around the station (vertical line). The distance variations relative to the station are shown in Figures 2e and 2f. The differences between the GIM and Topex are also very small (less than 2 TECU) within a 1000 km range. Beyond 1000 km, the differences increase with increasing distance. The Bent model exhibits larger discrepancies than GIM when comparing with Topex's observations. The two cases illustrate that GIM performs very well in the mid-latitude ionosphere within a 1000 km (corresponds to a 14° elevation angle cutoff; i.e., includes all GPS data above 14° elevation, and none below this angle) of GPS stations.

3.2 Statistical Analysis of Distance Dependence. We present the statistical results from a large database in Figures 3 - 6. In order to characterize the variations in GIM accuracy with distance to the closest GPS station, we have shown the difference between the GIM and Topex in TEC measurements as a function of distance for two cycles in Figure 3. The RMS values, which represent the map errors, are also shown using a +/- range around the means (i.e., the length of each error bar is twice the RMS value). The plots have a distance range of up to 4000 km with 200 km bins. In each 10-day cycle, Topex makes 254 passes around the earth (alternatively ascending and descending). On average, each distance bin has approximately 4000 data points. We have computed the distance to the nearest station for each TEC measurement of Topex and GIM along the trajectory. In the top panel of Figure 3 is the distance dependence for Cycle 18. We see that the average differences (ΔTEC) between the GIM and Topex measurements are less than 3.5 TECU out to a distance of 4000 km. The values gradually increase from 0.2 TECU at 100 km to 3.4 TECU at 4000 km. The RMS also increases from 5.8 TECU at 100 km to 12.5 TECU at 4000 km. The increase in RMS becomes significant at a distance of around 2000 km from the stations. Direct measurements from GPS are available below 1500 km, hence an average RMS of less than 8.0 TECU is observed within the range of 1500 km. Because there were larger geomagnetic disturbances during the cycle 18 period, it is not surprising that cycle 18's mean and RMS errors are larger than those in other cycles.

The lower panel in Figure 3 gives the variation of GIM accuracy with distance for Cycle 33. The GIM TEC measurements show a high accuracy (very small mean) and small RMS scatter around the mean. The average values of the differences between GIM and Topex TEC measurements are less than 1.0 TECU within the 2000 km range. The RMS gradually increases from 2.5 TECU at about 500 km distance to 6.5 TECU at 4000 km. The errors are half of those in cycle 18. Because there were lower solar flux and geomagnetic activity in cycle 33 than cycle 18, cycle 33 may represent a quiet ionosphere during solar declining period. Considering that the Topex altimeter's measurements are estimated to have errors of 2 - 3 TECU [Callahan, 1993; Imel, 1994], the means and RMS errors in Cycle 33 are very small. This suggests that GIM is capable of tracking the TEC over long distance quite accurately, when the ionosphere is relatively inactive. In effect, the GPS measurements can have an "extended range" of validity during quiet times, when the ionosphere is relatively time-stable in solar-magnetic coordinates.

The Bent model's performance in TEC predictions as a function of distance from GPS stations is shown for these two cycles in Figure 4. Because the Bent model requires only a few geophysical parameters (such as solar sunspot number, solar F10.7 flux, time, latitude, and longitude) independent of GPS measurements, we do not expect a distance dependence in its accuracy. Figure 4 illustrates this independence by the almost constant RMS. In cycle 18 (top panel), the RMS is constant, as high as 10 TECU through the entire distance range. The average difference between the Bent model and Topex in TEC measurements increases to 4.0 TECU in magnitude. In cycle 33 (lower panel) the mean is also significantly apart from the Topex measurements by > 4.0 TECU. The RMS is almost constant (6.5 TECU), independent of distance variation. TEC average values predicted by the Bent model in the two cycles are relatively lower than values measured by Topex. Because there is no upstream solar wind and geomagnetic index as input [Bent et al., 1976], the historical model performs significantly worse during active ionospheric conditions, which may become significant as we approach the next solar maximum.

We further divide Cycle 18 into three different latitude regions to see how the accuracy of GIM and the Bent model depend on distance within a 3000 km range. We have binned the global data by the geomagnetic latitude: northern hemispheric region (geomag. lat. > 30°), equatorial region (30° > geomag. lat. > -30°) and southern hemispheric region (geomag. lat. < -30°). The statistical results for the two techniques are shown in Figures 5 and 6 using 100 km bins. In Figure 5 we see GIM has higher accuracy in both the northern and southern hemispheres than in the equatorial region. In both regions, the RMS is very small (about 2.0 TECU) within the 1000 km range. Then the RMS increase to about 8.0 TECU at 3000 km away from the GPS stations. In the northern hemisphere, because there are more GPS stations, the distance between the Topex trajectories and the GPS stations is rarely greater than 3000 km. Thus up to 2000 km, GIM performs extremely well and the average values of the differences between GIM and Topex are quite small in all distance ranges. In the equatorial region, because of the Appleton anomaly and fewer GPS stations, the agreement is not as good. A positive mean around 3.8 TECU indicates that GIM values are on average greater than Topex measurements in the equatorial region. Since TEC values measured by GPS include the contribution from the plasmasphere, one expects a positive bias between GIM and Topex.

There is no distance dependence for the Bent model's accuracy in TEC prediction as shown in Figure 6. In both northern and southern hemispheres, the RMS is nearly constant at about 7.0 TECU within the 3000 km range. In the equatorial region, the RMS is almost double (13.8 TECU) indicating that Bent does not accurately follow the larger TEC variations in that region. A negative mean (-5.9 TECU) shows that the Bent model prediction is lower than TEC values measured by Topex.

Because GIM prediction is mainly determined by TEC measurements from the nearest GPS station, we expect GIM to exhibit a dependence on distance. We find that the difference between the GIM and Topex TEC measurements is very small on average. Within a 2000 km (elevation angle > 1.0°) range, this difference is less than 1.2 TECU. Within a 1000 km range (elevation angle > 15°), the RMS is almost constant. However, the RMS ranges also depend on solar activity and ionospheric TEC values. For the Bent model, its accuracy in TEC measurements has no relation to GPS stations, so there should be no dependence on distance. Its RMS should be constant over this large distance range. The statistical results are consistent with these expectations.

3.3 *TEC correlations with Topex measurements.* Next we compute the correlations between Topex and measurements from GIM versus the predictions from the Bent model as a function of increasing ionospheric TEC for two Topex cycles. These statistical results are shown in Figures 7 - 10 for two distance ranges (0 - 1000 km and 1000 - 2000 km) and three latitude regions. A linear fit to a data set may be described by the correlation coefficient (R), the slope of the best fit line and the RMS scatter (S). If GIM measurements fit the Topex data very well, we should expect to see a high correlation coefficient (R~1.0), an ideal slope near 1.0 (45.0°) and a small error when the numbers of data samples are comparable. Figures 7, and 8 give the TEC measurements of GIM versus Topex for cycle 18, and 33. In general, we find that GIM values have a good linear relation to the Topex values within a 1000 km range in two latitude regions. In the two cycles, all correlation coefficients are greater than 0.93. GIM has reduced performance in the distance range between 1000 km and 2000 km and in both the equatorial and southern latitude regions. However, in the northern hemispheric regions GIM fits closely the Topex measurements. The correlation coefficients are high (> 0.95) and the scatters (S) is small. As a comparison, the Bent model predictions have lower correlation coefficients with the Topex measurements as shown in Figures 9 and 10. A significant feature is that the values predicted by Bent are often systematically lower at larger TEC values. We can see this cut-off phenomenon clearly in the equatorial regions for the two cycles. In cycle 18 the Bent model is cut off at about 80 TECU, for cycle 33 at 40 TECU. It is this saturation which causes the poor linear fit. This characteristic of the Bent model does not bode well for its predictive power during more active ionospheric conditions, such as during magnetic storms and near solar maximum. Generally, due to the saturation the Bent model TEC values are lower than the Topex measurements. All of the fitting parameters for the two cycles and both techniques are listed in Table 2. Statistical results are shown in three geomagnetic latitude regions: northern hemispheric, equatorial and southern hemispheric regions. There are higher correlation coefficients (R) between GIM and Topex than between Bent and Topex in TEC measurements. The average slope of the linear fit for GIM measurements is 44.5°. This is very close to the "ideal" 45.0°. The average slope for the Bent model is 38.5°. For 0 - 1000 km, GIM errors (in TECU unit) are almost always lower than those for Bent, while for 1000 - 2000 km, the two are more comparable.

4. Discussion

As we stated before, one of the advantages of the GIM technique is that a global TEC specification may be generated hourly or more often, while Topex will require about 60 days of data to generate such a global map to cover all local times. However, along the Topex track, the altimeter data does provide high resolution measurements of the ionospheric TEC. Because the Bent model comes from average values based on past measurements over several years, it is generally a good long term average, but has less sensitivity to small spatial and temporal variations. Due to the global distribution of GPS stations and continuous operation, GIM measurements are better suited for the accurate study of global and large-scale ionospheric structures than both Topex data and the Bent model.

We find that the relatively large RMS between GIM and Topex in cycle 18, shown in Figure 3 is due to a few large outliers. These outliers show the existence of some big differences (> 30 TECU) between the GIM and Topex in TEC measurements. After carefully examining these data, we found that these large differences come mainly from two types of data. One represents some artificial over-shoot spikes generated by GIM fitting techniques relative to the smoothly varying Topex measurements. The others are smooth profiles measured by GIM while Topex detects some narrow transient TEC peaks. The former discrepancy may be reduced by improving GIM fitting techniques, in particular, by regularizing the maps with simulated data (already in progress, see Mannucci et al., 1977). But not much can we be done about the latter discrepancy at this stage just simply because we do not have enough GPS stations to resolve such small spatial variations (as the global network keeps growing, this problem will diminish).

There are several sources of errors which lower the accuracy of GIM measurements [Klobuchar et al., 1993]. One is the instrumental biases from the GPS system [Wilson and Mannucci, 1993], which include both the satellite biases and receiver biases [Sardon et al., 1994]. Multi-path of signal propagation at low elevation angles can also cause errors in determining LOS TEC values. Another error comes from mapping the TEC values to vertical under an assumption of a shell ionosphere with constant peak height. If the ionosphere has a horizontal gradient, mapping to vertical will produce large errors because the correct IPP location is poorly determined by the fixed shell height assumption. Such errors are probably largest due to the Appletion anomaly at low latitude. The total errors are estimated to have an upper limit of about 5.0 TECU.

The statistical results show that the GIM technique has reduced performance in the equatorial and southern hemispheric regions. Within 1000 km of the nearest station, only the low-latitude accuracy is significantly worse, probably because of the inadequacies of the shell model in the presence of large latitudinal gradients or transient variations in ionospheric structure which cannot be effectively followed. At the larger distances (1000-2000 km), even the southern latitudes are worse than the north. Assuming comparable ionospheric structure in the mid-latitudes (north or south), this may be due to the small number of GPS stations located in this area, particularly back in 1993 (cycles 18 and 33). Although we have computed the statistics taking the nearest receiver into account, it is possible that improved results are obtained when the nearest receiver is part of a cluster that produces simultaneous overlapping measurements of a region. In the north, the same minimum distance may nevertheless include several receivers within comparable distances, adding to the strength of the solution. For sparsely populated latitude bands, the nearest receiver may be the only receiver that contributes significantly, and the reduced data strength leads to less accuracy.

In 1993, only four GPS stations were available in the low-latitude region. Based on the results of Figures 3 and 5, direct measurements from GPS available within 1500 km (7° elevation angle) would provide fairly precise mapping. Globally, if the distance between any two global network stations is reduced to 3000 km (27° in latitude or longitude about the equator), GIM will have very good correlation with the Topex measurements everywhere.

We need to further characterize the GIM performance during ionospheric or geomagnetic storm periods. During these periods, the ionosphere becomes more irregular. In the database we have examined cycle 18 which includes three small storms. A preliminary survey reveals that there are a number of outliers between GIM TEC measurements that are not consistent with Topex observables. We need to identify whether each outlier comes from real GIM observations or is due to interpolation error or an error in the Topex data. In the near future we will use the near real-time GPS data to nowcast the ionospheric storms by using global TEC onset signatures.

5. Summary

For the first time, we have performed a comprehensive statistical study of the performance of a GPS data-driven model as compared to a climatological model. We have compared the agreements of the GIM and the Bent model with Topex altimiter data (used as a source of ground truth for ionospheric TEC measurements). From this study the following conclusions have been drawn:

1. The data driven (GIM) technique has much better performance than the predictions of the historical data (Bent) model under most conditions. The average difference between GIM and Topex in TEC values is very small (less than 1.5 TECU) within a 2000 km range. The RMS gradually increases with an increasing distance from the GPS station and approaches the Bent results (while the Bent model shows no such distance dependence with a constant large RMS).

2. The data driven (GIM) technique has significantly higher accuracy than the Bent model in specifying the ionosphere. Within a 1000 km distance range (elevation angle > 14°), GIM has a good correlation (R > 0.93) to Topex in TEC measurements. The average slope is 44.5° (near the ideal 45°). The Bent model shows a poor linear fit with lower correlation coefficients in the same distance range.

3. GIM is quite accurate up to 2000 km distances (~ 1° elevation angle). Beyond 2000 km, GIM accuracy on average is reduced to the Bent model levels. This suggests that the GIM was unable to track ionosphere changes in regions with sparse or no data. As a result, the data driven model (GIM) is more accurate in the northern hemisphere where there are more stations.

4. Note that in the equatorial region, the data driven model also performs better than the Bent model. The Bent model predictions are on average lower (~ 5.0 TECU) than Topex values and often show a saturation at large TEC values. During ionospheric disturbed periods, GIM sometimes shows larger differences from Topex values due to untracked transient variations of the ionosphere.

5. Through a spatial and temporal interpolation, TEC values may be filled in those regions beyond 2000 km from each GPS station. A global ionospheric TEC map can be made every 15 minutes (or more frequently). This GIM technique will provide a powerful tool for specifying the global ionospheric features.

In conclusion, the Bent model generally will calibrate ionospheric delay with 20-50% errors. The largest errors occur near the equator during active ionosphere. The data driven (GIM) approach is clearly superior with vertical TEC errors generally between 3-10 TECU or at the 10-20% error level (when compared with the maximum daytime signal strength).

These errors are expected to decrease as more GPS stations come on-line, especially in the equatorial regions, and as the data-driven GIM algorithm improves with time.

Acknowledgments: We thank M. Reyes for his help in data analyses. The research conducted at the Jet Propulsion Laboratory, California Institute of Technology was performed under contract to the National Aeronautics and Space Administration.

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Figure Captions

Figure 1. Relationships between the horizontal distance in the ionospheric height, zenith angle, elevation angle and geocentric angles relative to the GPS station.

Figure 2. Two typical cases to show the differences in TEC measurements by Topex, GIM and the Bent model along the Topex trajectories. Case 1 is shown in a) latitude scan, b) distance variation, and c) differences between three techniques. Case 2 also is given in d) latitude scan, e) distance variation, and f) differences between three techniques.

Figure 3. Differences between GIM and Topex in TEC measurements as a function of distance from GPS stations: Cycle 18 (top) and cycle 33 (bottom).

Figure 4. Differences between the Bent model and Topex in TEC measurements as a function of distance from GPS stations: Cycle 18 (top) and cycle 33 (bottom).

Figure 5. Differences between GIM and Topex in TEC measurements as a function of distance from GPS stations for Cycle 18 in three latitude ranges: Northern hemisphere (top), equatorial region (middle) and southern hemisphere (bottom).

Figure 6. Differences between the Bent model and Topex in TEC measurements as a function of distance from GPS stations for Cycle 18 in three latitude ranges: Northern hemisphere (top), equatorial region (middle) and southern hemisphere (bottom).

Figure 7. Correlation between GIM and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 18. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

Figure 8. Correlation between GIM and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 33. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

Figure 9. Correlation between the Bent model and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 18. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

Figure 10. Correlation between the Bent model and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 33. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

Table 1. Average Geophysical Conditions for Three Cycles

Cycle No.	18	33	88
Time Intervals	Mar. 10-20,1993	Aug. 6-16,1993	Feb.2-12,1995
Dst (nT)	-40.5	-11.0	-25.2
Daily Kp	29.2	17.1	21.9
F10.7cm Flux (10^{-22}Joules/s/m^2/Hz)	1370	937	848

Table 2. Correlations between GIM, Bent Model and Topex
in Ionospheric TEC Measurements

Cycle 18		North			Equator			South		
March 10-20,1993		R	Slope	Error	R	Slope	Error	R	Slope	Error
0 - 1000 km	**GIM**	**0.98**	**45.0°**	**2.62**	**0.95**	**45.8°**	**7.39**	**0.97**	**47.5°**	**3.18**
	Bent	0.91	42.0°	6.00	0.87	39.0°	10.32	0.81	38.7°	6.55
1000 - 2000 km	**GIM**	**0.97**	**46.4°**	**3.65**	**0.88**	**42.6°**	**11.02**	**0.87**	**43.2°**	**6.01**
	Bent	0.91	42.3°	5.43	0.83	34.2°	10.25	0.80	35.0°	6.05

Cycle 33		North			Equator			South		
August 6-16,1993		R	Slope	Error	R	Slope	Error	R	Slope	Error
0 - 1000 km	**GIM**	**0.97**	**48.5°**	**2.01**	**0.96**	**45.8°**	**3.42**	**0.93**	**43.5°**	**1.85**
	Bent	0.89	39.0°	2.84	0.90	41.7°	5.04	0.92	33.4°	1.45
1000 - 2000 km	**GIM**	**0.95**	**48.5°**	**2.37**	**0.94**	**47.2°**	**4.94**	**0.80**	**40.7°**	**3.27**
	Bent	0.90	36.5°	2.42	0.94	40.7°	3.98	0.86	29.7°	1.69

Horizontal Distance from Station, Zenith Angle, Elevation Angle, and Geocentric Angle

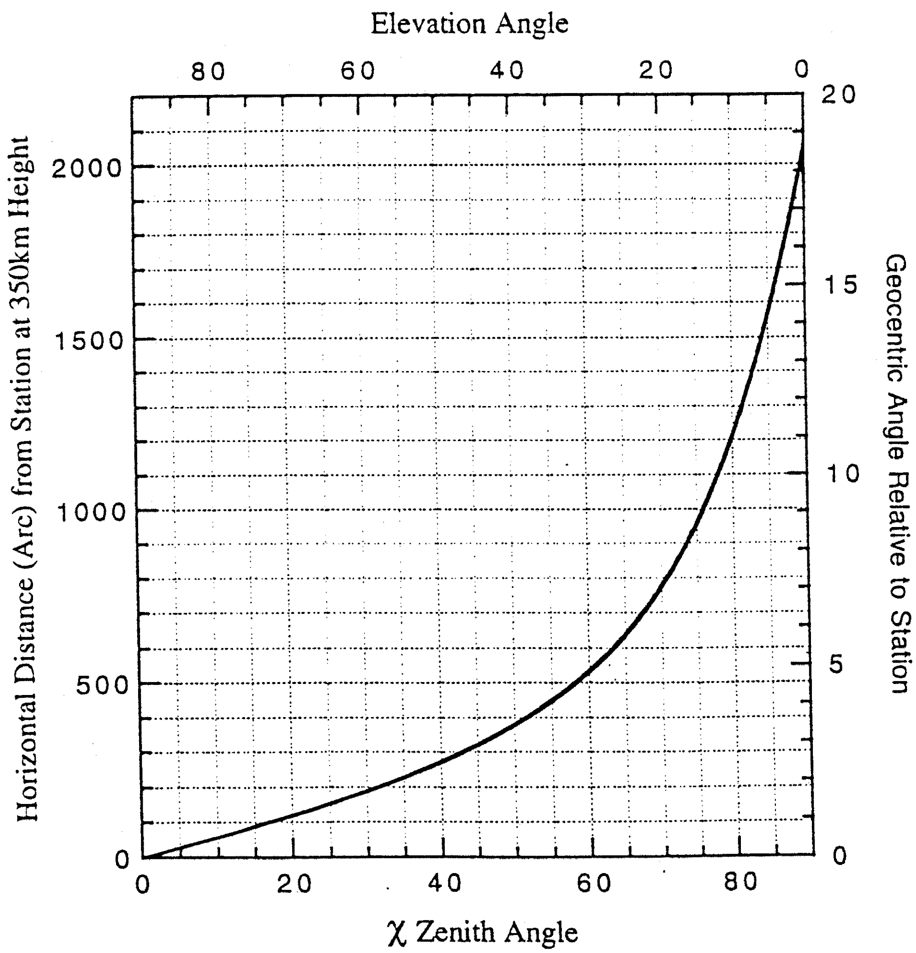
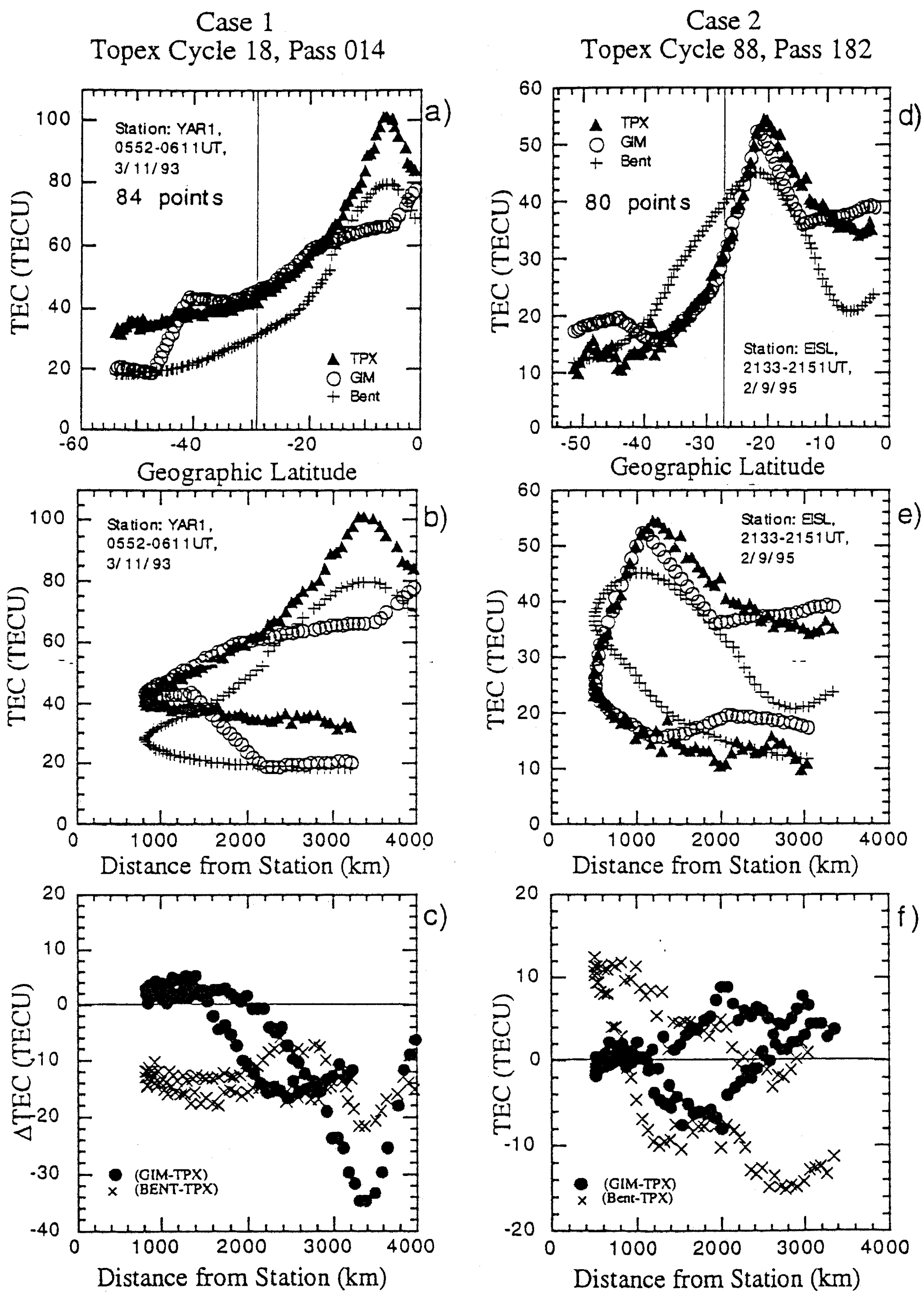


Figure 1. Relationships between the horizontal distance to the ionospheric height, zenith angle, elevation angle and geocentric angles.



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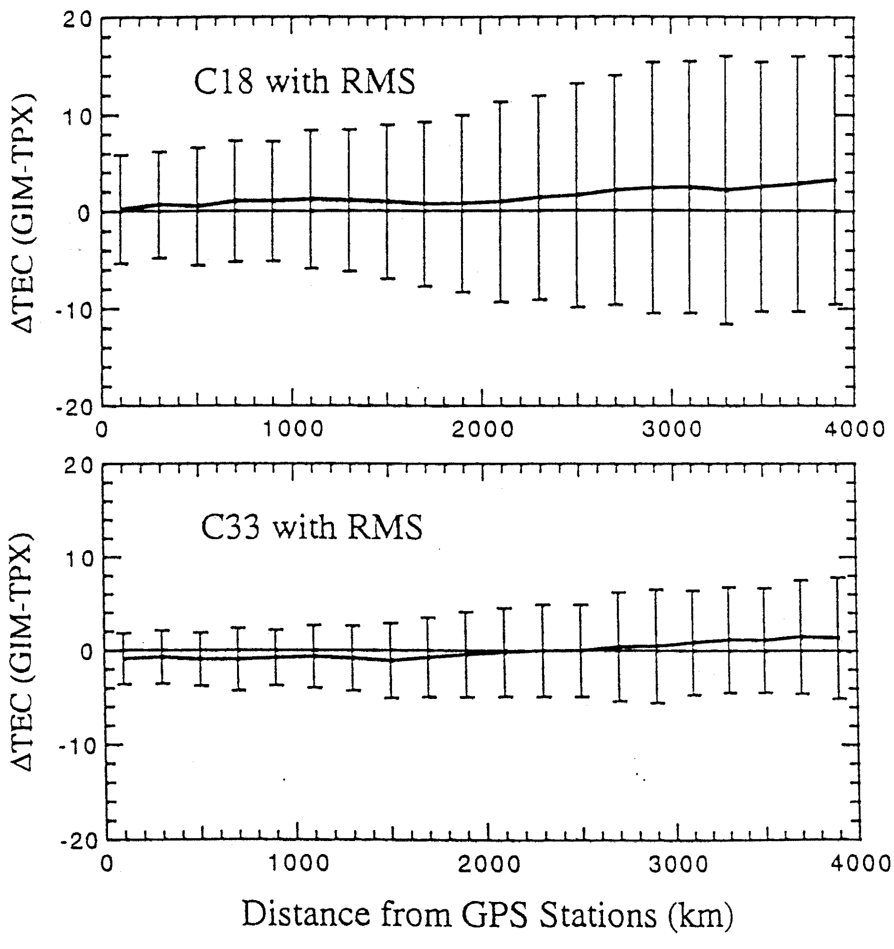

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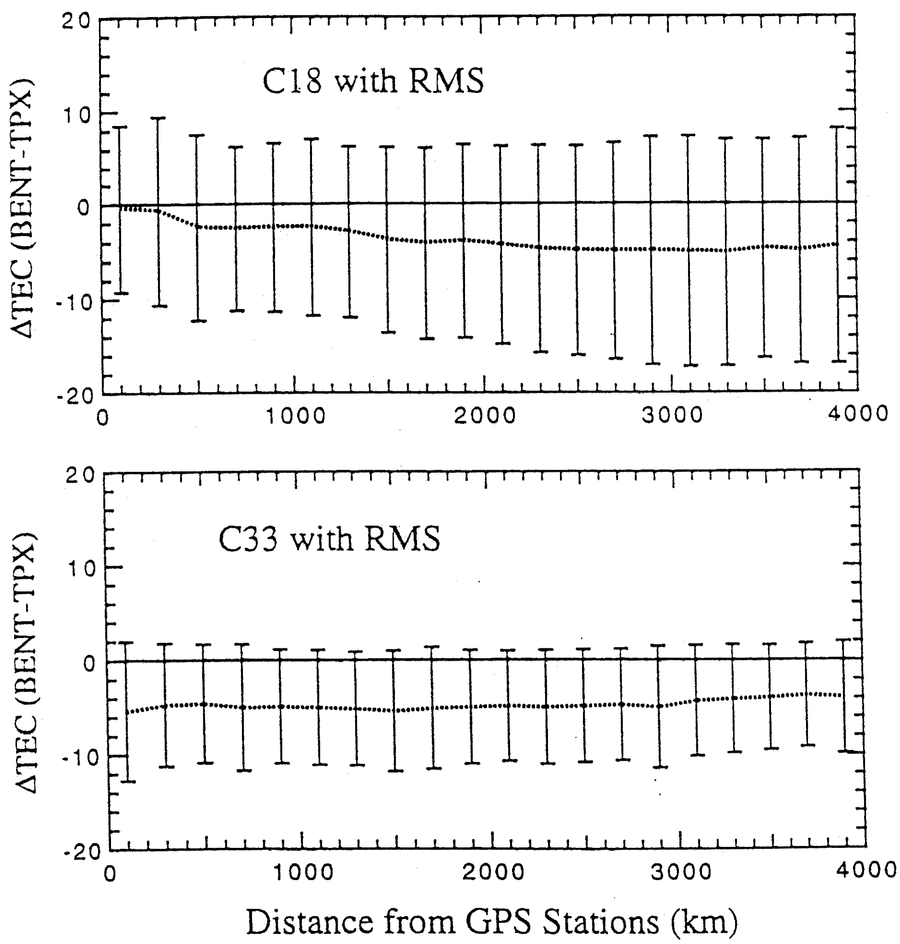

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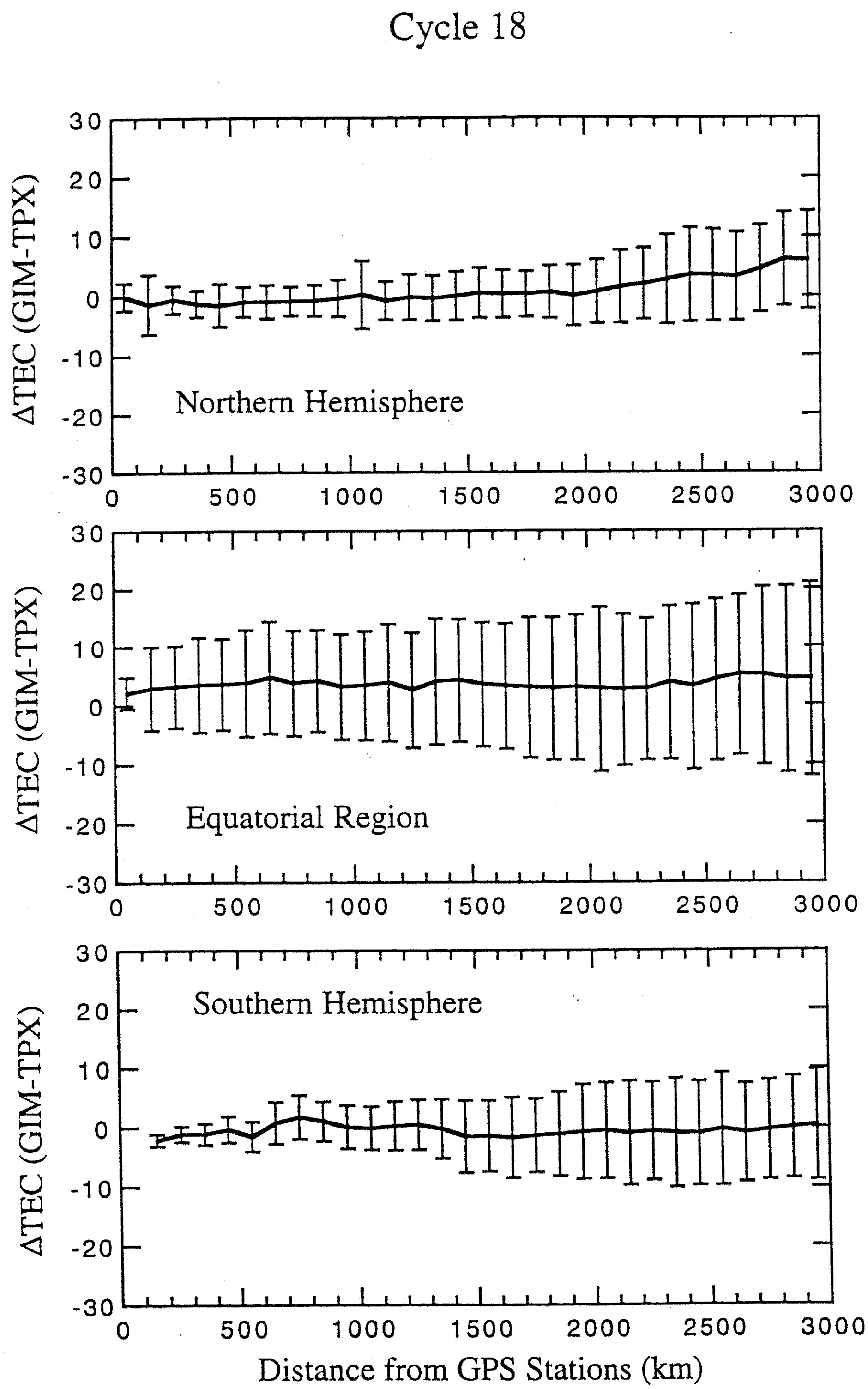

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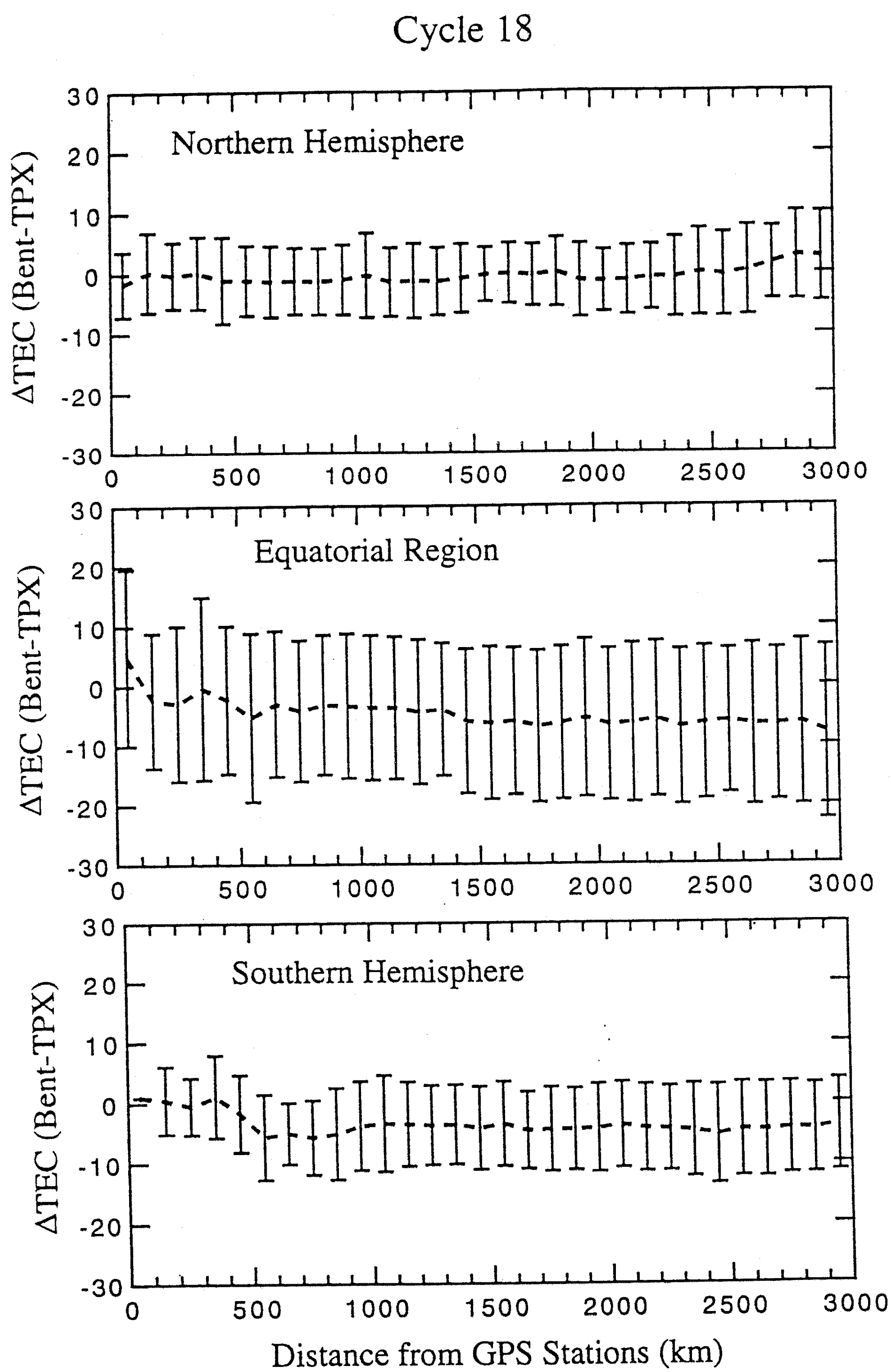

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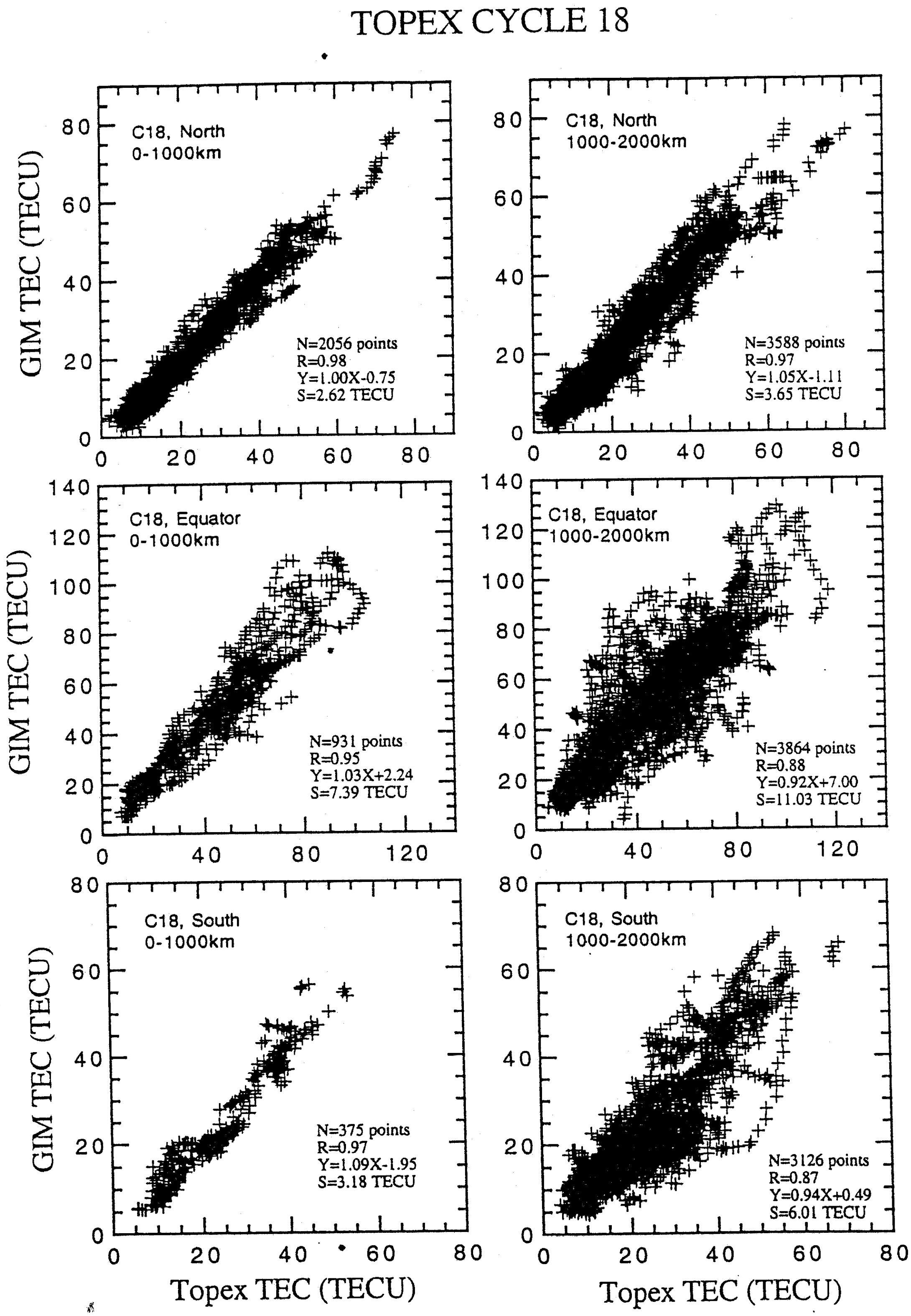

Figure 7. Correlation between GIM and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 18. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

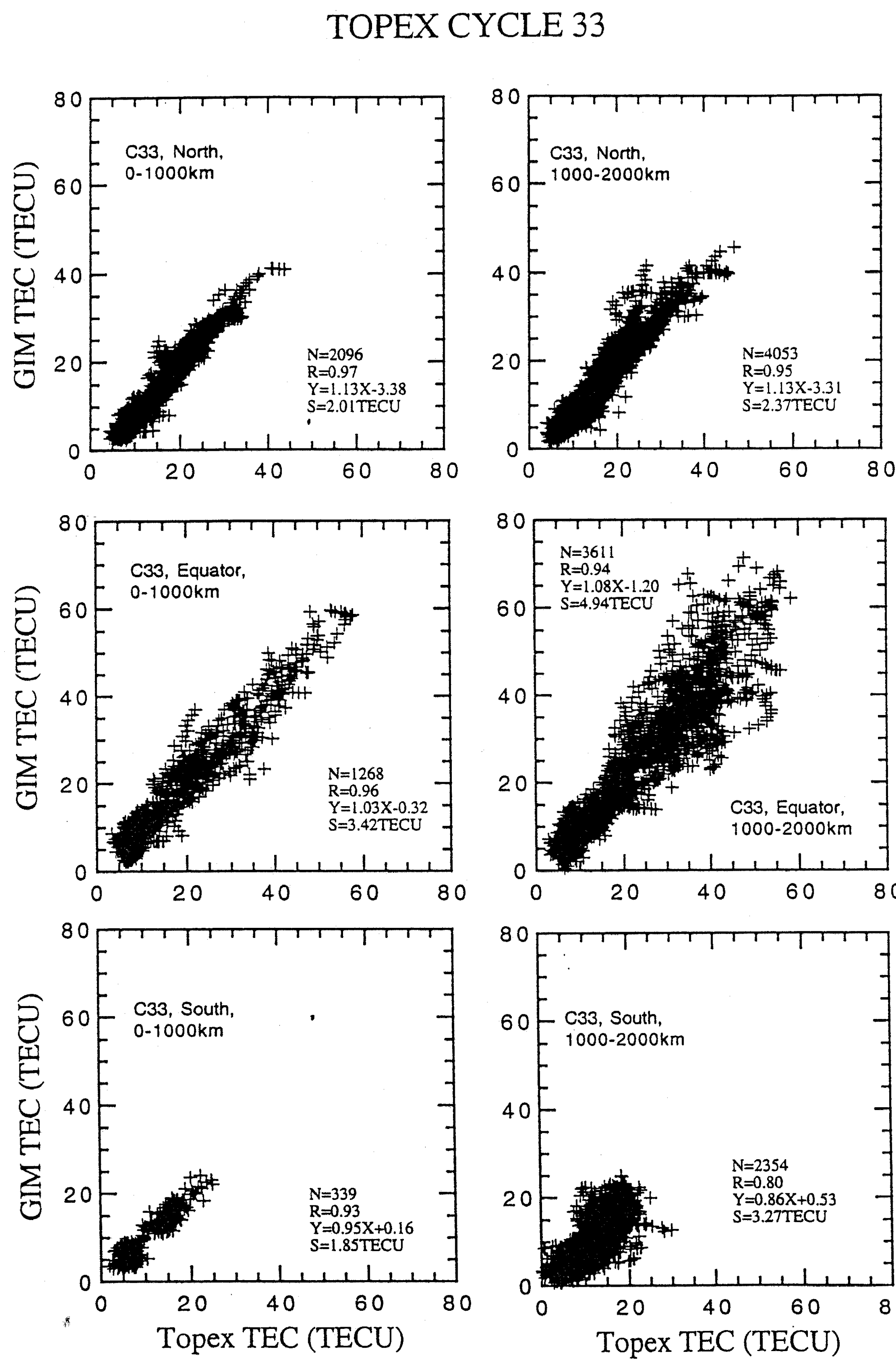

Figure 8. Correlation between GIM and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 33. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

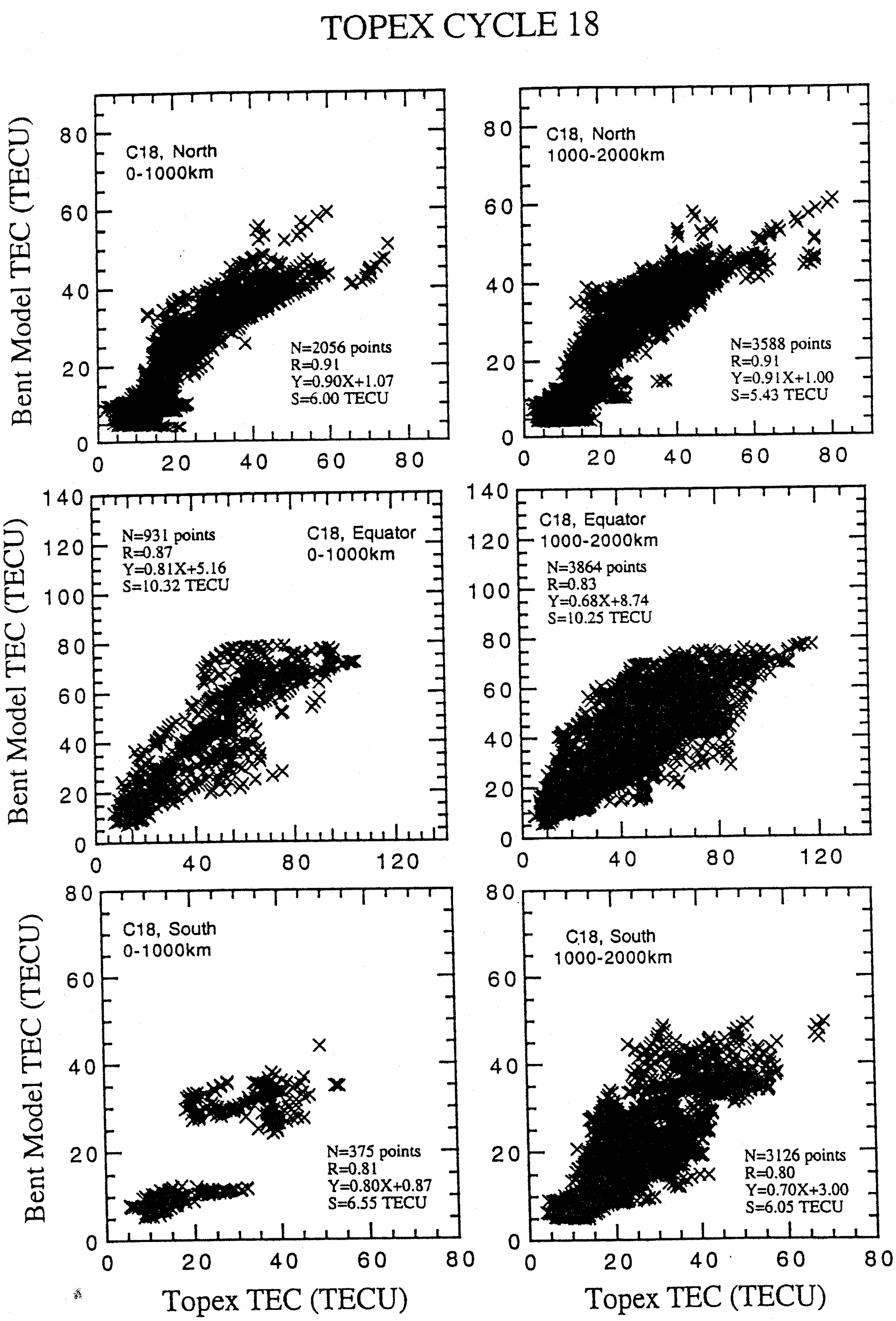

Figure 9. Correlation between the Bent model and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 18. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.

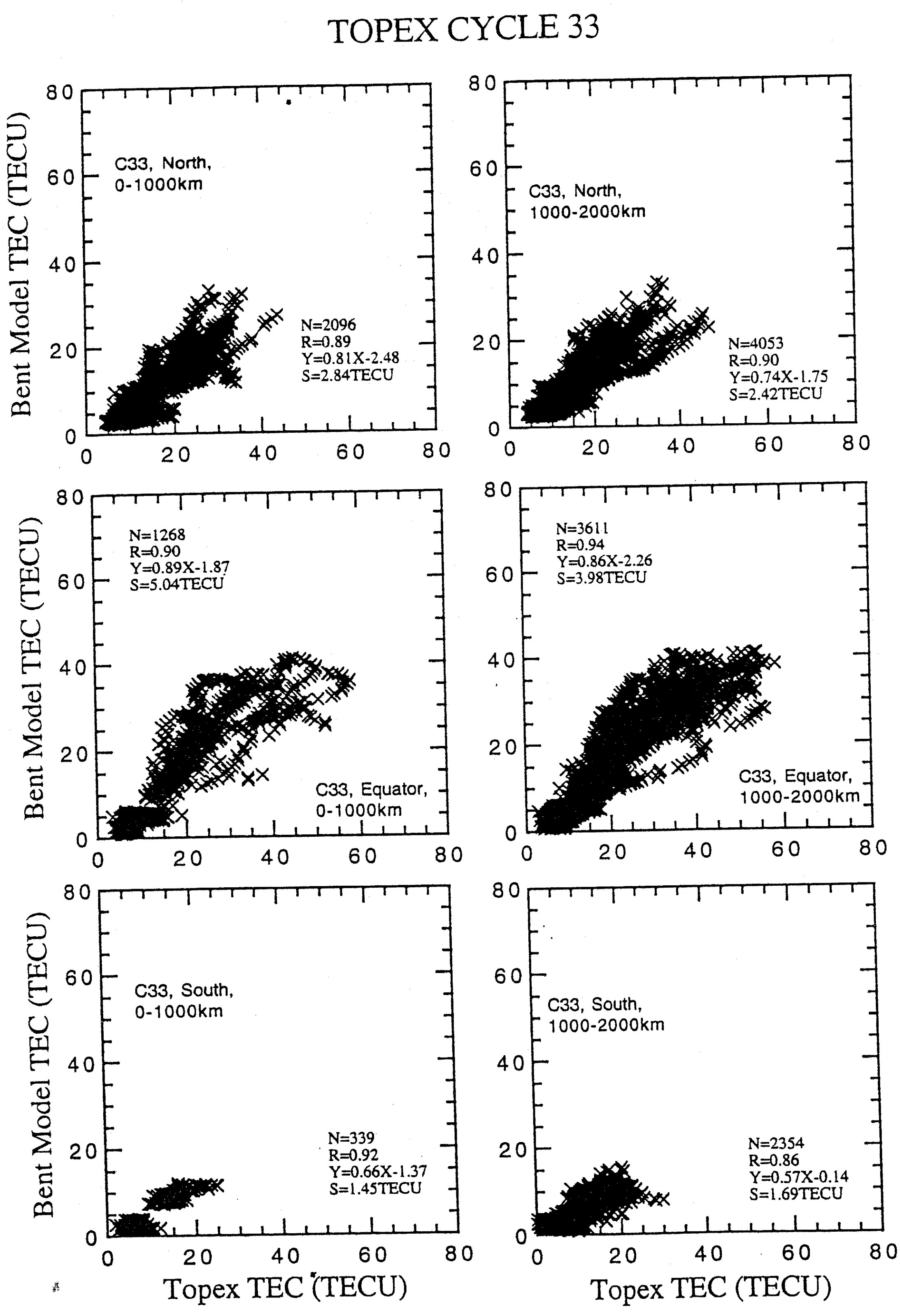

Figure 10. Correlation between the Bent model and Topex in TEC measurements in two difference distance ranges and in three latitude regions for Cycle 33. Correlation coefficients, linear fit parameters and scattering errors are shown in each plot.